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Geomorphic indexing of landslide dams evolution

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ABSTRACT

Landslide dams are rather common events in hilly and mountainous areas and they occur when a landslide reaches a valley floor closing the riverbed. If they form a lake basin, unstable landslide dams can have catastrophic consequences when they occur in upstream of populated regions. Landslide dam behavior is not completely understood yet, however several studies suggested implementing geomorphological index in order to assess their formation and evolution. These indexes result from the composition of two or more morphological attributes that characterize the landslide (e.g. landslide volume or length) and the involved river valley (e.g. valley width).
The objective of this work is the definition of a procedure, based on the joint use of different indexes, to assess landslide dams evolution over large areas (e.g. entire river catchment or even a region or a nation) and in short times, in order to be used for emergency response or for planning activities.
About 300 landslide dam events collected in Italy were analyzed and some state-of-the-art geomorphological indexes were applied to characterize the damming phenomena at the national scale. To overcome some limitations of the aforementioned indexes, we introduce two new indexes: the Morphological Obstruction Index and the Hydromorphological Dam Stability Index. The former combines the river width and the landslide volume, and it can be used to identify the conditions associated to dam formation discriminating between circumstances where a landslide dam is formed and circumstances where it is not. The latter uses a simplified stream power formulation (combining the upstream catchment area and the local slope gradient) to account for the river energy. This index allows evaluating the stability of a dam in near real time as soon as it occurs and can be used to discriminate between stable and unstable dams.
If compared with the reviewed state of the art indexes, the newly proposed ones show an improvement in the forecasting effectiveness and have the advantage of being based on morphometric input parameters that can be easily and quickly assessed on a distributed way even over large areas. We propose a tool that is based on the joint use of the newly proposed indexes and that can be used to provide fast and effective assessment on landslide dam formation and stability during emergency or planning activities.

1. Introduction

Landslides involving river channels can alter the hydrological dynamics, up to the extreme consequence of the stream blockage (Costa and Schuster, 1988; Canuti et al., 1998; Ermini and Casagli, 2003; Korup et al., 2006). If the sliding materials are not able to completely block the riverbed, the impact on the fluvial network is usually limited. Conversely, when the obstruction is complete, it may originate dammed lakes and upstream areas may be flooded over kilometers, as the 60 km long lake formed by the Usoi landslide dam, Tajikistan, in 1911 (Schuster and Alford, 2004). If the dam is stable, the basin can last even for centuries until sediments fill it, otherwise the dam can collapse causing serious hazard to life and property. In downstream areas, a dam breach may lead to destructive events, such as anomalous flood waves, which can generate lasting effects on the natural environment and infrastructures. One of the worst historical flooding events is the breaching of the seismic induced dam on the Daru River, China, in 1786, with over 100,000 fatalities (Dai et al., 2005).

Since in many countries the human settlements and activities are mainly established in valley floors, the consequences can be tragic, causing significant economic damages and casualties (Pirocchi, 1992; Casagli and Ermini, 1999). These situations can be limited through accurate urban planning and flood risk management (Van Herk et al., 2011; Plate, 2002). However, in the international literature it has never been established a tool for the fast and effective assessment of the river obstruction and of the dam stability, to be used over large areas for emergency response or to forecast hazard scenarios.

In Italy, characterized by a wide geological, morphological and climatic variability, landslide dams and related flooding are rather

Abbreviations: DataBase, Italian Landslide Dams Database (Tacconi Stefanelli et al., 2015); BI, Blockage Index; ACR, Annual Constriction Ratio; DBI, Dimensionless Blockage Index; MOI, Morphological Obstruction Index; HDSI, Hydromorphological Dam Stability Index.

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frequent (Guzzetti and Tonelli, 2004; Salvati et al., 2010). Nevertheless, the scientific study about this topic has started only after the impressive episode of Val Pola (Sondrio, Northern Italy) event in 1987, when a huge landslide of 40 Mm^3 completely blocked the valley floor and the consequent evolution resulted in 29 casualties (Govi et al., 2002; Crosta et al., 2004). After this event, some authors compiled landslide dams inventories covering different portions of the Italian territory (Pirocchi, 1992; Casagli and Ermini, 1999; Coico et al., 2013) at different scales and with different standards of detail. Tacconi Stefanelli et al. (2015) homogenized these inventories and new data to set a national-scale archive of 300 landslide dams occurred in Italy, with their main morphometric parameters. Other examples of national scale inventories of landslide dams are those built in New Zealand (Korup, 2004), China (Peng and Zhang, 2012) or Switzerland (Bonnard, 2011).

Existing landslide dam databases are a fundamental resource, since the analysis of past events represents a fundamental step to identify which parameters played a role in their formation and evolution. A common methodology used in quantitative geomorphological analysis is to employ morphometric relationships (Strahler, 1957; Troiani and Della Seta, 2008; Font et al., 2010; Larsen et al., 2010). According to some studies, geomorphological indexes can be used to assess landsldie dam formation and evolution (Swanson et al., 1986; Ermini and Casagli, 2003; Korup, 2004; Cui et al., 2009; Dong et al., 2011; Fan et al., 2012; Peng and Zhang, 2012; Dal Sasso et al., 2014). Geomorphological indexes are composed by variables characterizing the different involved elements (the landslide, the dam, the valley, the river and the lake) and aim at simulating their interactions in a complex geomorphological system. Moreover, concerning practical applications, indexes with high significance can be used to forecast and discriminate between possible dam evolutions. Many geomorphological indexes are used in studies focusing on a single landslide dam (Hermanns et al., 2004; Nash et al., 2008; Duman, 2009). Although some of these indexes can be conveniently used in local scale applications, their use over broad areas (e.g. in national scale studies) is problematic. This is especially true for those indexes that are based on parameters (e.g. peak flow, dam's material granulometry) that can be assessed with sufficient accuracy only by punctual measurement, and their definition for many occurrences over a broad area is troublesome (Ermini et al., 2006; Dong et al., 2011; Dal Sasso et al., 2014). Neither they can be easily defined on a distributed way over an entire area in order to make prevention nor to assist planning activities.

When the object of the study is the characterization of the many landslides involved in a large dataset, the employ of parameters derived from distributed data (e.g. the drainage area from a DTM) and the selection of simple relationships is preferable (Costa and Schuster, 1988; Ermini and Casagli, 2003; Korup, 2004). Regarding this issue, Swanson et al. (1986) proposed two indexes through the analysis of several phenomena occurred in Japan: the Blockage Index and the Annual Constriction Ratio, both able to evaluate the landslide dam formation. Analyzing landslide dams in North Apennine, Italy, Ermini and Casagli (2002) proposed a refined version of the Blockage Index with a dimensionless formulation. Their Dimensionless Blockage Index was used to assess effectively the dam stability and evolution.

The final objective of this paper is the definition of a tool, based on the joint use of geomorphological indexes, to understand the potential evolution of landslide damming phenomena and to be used over large areas for emergency response or to assist planning activities. First, we explore the applicability at national scale of some state-of-the-art indexes on the Italian national database built by Tacconi Stefanelli et al. (2015). Then, we propose and apply to the same database two new geomorphological indexes. On one hand, the new indexes have improved forecasting effectiveness. On the other hand, these indexes are based on morphometric parameters that meet the basic principles of easy and fast data collection. Finally, we propose a combination of both indexes in order to define a tool that could be effectively used to forecast hazard scenarios for planning activities or for emergency response, in applications ranging from the local to the national scale.

2. Materials and methods

2.1. The dataset

Italy is a country endowed with a wide climatic, geological and morphological variability, manifested in high precipitations (Alps and Northern Apennine), tectonic uplift (Alps), and volcanic activity (Southern Apennine). Alps are glaciated areas with very high energy of relief and slope gradients, with elevation of up to 4000 m a.s.l. Apennines are characterized by highly variable morphology and sensible precipitation differences from north to south. A general seismic activity is present in all the Italian territory.

In this work we analyze past landslide dam events recorded in Italy, using the single most complete inventory of Italian landslide dams provided by Tacconi Stefanelli et al. (2015) (hereafter DataBase) as input data. The inventory was derived from heterogeneous sources, extensively revised, homogenized, updated and completed. It was realized through aerial photointerpretation, cartographic analysis or historical and bibliographical research and consists of 300 comparable events in all Italy. The DataBase characterizes each case with a series of morphometric parameters, including the length and volume of the landslides and the dams, the river valley width, the riverbed slope and the basin catchment area. All of them were measured through cartographic and aerial image interpretation, or estimated through historical and bibliographical data research.

In the DataBase landslide dams are subdivided in three classes, which represent the three possible final stages of their long-term evolution:

- Not-formed: the landslide reached the riverbed but, although the river flow could have been altered, the riverbed section is only reduced realizing a partial damming of the stream. The upstream lake basin did not formed and the further evolution can be a river deviation or landslide toe erosion.
- Formed-unstable: the landslide completely blocked the river, forming a natural dam and an upstream lake. However, over times that can range from hours to centuries, the dam collapsed or was breached by the river. A high level of hazard is usually associated to this class, because collapses and breaches can be associated to sudden flooding waves. A dam was classified as formed-unstable also if it was artificially stabilized or removed, because it is supposed that such interventions take place only after that a careful evaluation points out the potential instability of the landslide dam.
- Formed-stable: the blockage was complete with the formation of a dam and a lake, which are still existing or disappeared for sediment filling. The dam could have been overtopped during its life, but no total failure or destructive flooding wave occurred.

These three classes represent all the possible evolutions of a process that evolves through two distinct steps. The first step is the dam formation: either the landslide does not form a dam or the landslide forms a dam. In the first case, we have the “not formed” class. In the second case, we move to the second step, where the formed dams are discriminated between those that collapse after a given period (“formed unstable” class) and those that are potentially everlasting (“formed stable” class).

The most frequent dams described in the DataBase are the formed-stable dams with 39%, the not formed dams are 33% and the formed-unstable 28%. This distribution does not reflect the real distribution of landslide dams in Italy: historical data and landscape analysis underestimate landslides with not-formed dams and small formed-unstable events without any social or environmental consequence, since they have not been recorded and their traces have been easily erased. However, the biased sampled population of the dataset does not influence our analysis, which is aimed at identifying the morphological features to discriminate between different categories of dam evolution. From this point of view, each of the three categories is well represented in the DataBase and thus can be consistently analyzed, characterized and compared with the others.

2.2. Existing geomorphological indexes

Some geomorphological indexes from the literature are reviewed in order to study the landslide dam formation and evolution. This allowed to evaluate which parameters best represent the evolution of the damming process. All the parameters employed by these indexes meet the principles of easy and fast data collection that are essential for the purpose of this study.

2.2.1. Blockage Index

According to Swanson et al. (1986), in order to assess the chance of dam stability, the landslide volume, V_l (m^3), and the hydrographic subtended surface, A_b (km^2), are the variables that best identifies the dam and the watercourse energy. Canuti et al. (1998) revised the study of Swanson et al. (1986) and proposed to take into account only the material that actually contributes to the formation of the dam, V_d, instead of the entire volume of the landslide, V_l. Thus, the formulation of the Blockage Index is expressed as follows:

$$BI = \log(V_d/A_b) \tag{1}$$

where V_d is the dam volume (m^3) and A_b the upstream catchment area at the point of blockage (km^2).

2.2.2. Annual Constriction Ratio

When a landslide reaches the valley floor, the blockage likelihood depends on the speed of the movement compared with the width of the valley floor. In their study, taking into account some landslides in Japan, Swanson et al. (1986) proposed the Annual Constriction Ratio, ACR, expressed as follows:

$$ACR = \log(W_v/v) \tag{2}$$

where W_v is the width of the dammed valley (m) and v the landslide velocity (m/s).

Usually, it is not possible to directly measure the landslide velocity. The landslide movement speed was estimated using the scale proposed by Cruden and Varnes (1996), based on the observation of the reported landslide effects. In their work, Cruden and Varnes (1996) established a relationship between landslide levels of damage and speed thresholds of the sliding mass.

2.2.3. Dimensionless Blockage Index

Introducing the dam height in the equation, Ermini and Casagli (2002) proposed a different dimensionless formulation of the Blockage Index, named “Dimensionless Blockage Index”, DBI:

$$DBI = \log\left(\frac{A_b \cdot H_d}{V_d}\right) \tag{3}$$

where H_d represents the dam height (m), V_d the landslide dam volume (m^3) and A_b the catchment area (km^2).

The volume is a parameter that well identifies the dam and when it increases, usually the global stability increases as well. According to their study, dam height is an important variable to assess the stability of a landslide dam against both overtopping and piping failure mechanisms. It influences the steepness of the dam slopes in the overtopping mechanisms, while it controls the hydraulic gradient in the piping mechanisms (Ermini and Casagli, 2003). This index does not consider not-formed or partial dams, because the height of a partially damming case can be subjective and misleading.

2.3. New geomorphological indexes

The landslide volume is one of the most influential parameter in the dam formation and stability (Swanson et al., 1986; Costa and Schuster, 1988). For the damming assessment, it is very important to identify the boundary characteristics of a landslide blocking a river valley. The morphometric data survey required for the study and the processing of the past landslide dams evolution, led to some degree of error, proportional to the amount of eroded material. The loss of relative volume, and thus the percentage error, is smaller if compared to the total landslide volume, rather than to the dam volume.

The volume distribution of the landslide dams in the DataBase, according to their evolution, is shown in the histogram of Fig. 1. In this simple diagram, landslides trend to instability or non-formation with small volumes, while the persistence of the dam prevails for large volumes.

From the observation of the DataBase, it is possible to asses that the evolution of damming phenomenon can be framed as a process with scale invariance. Dams can form starting from the smallest forms of channeled runoff, up to the larger rivers. In the DataBase, the dams volume are in range from 10^3 to 10^8 m^3 and rivers with catchment areas of variable extension from 1 to 10^3 km^2. Whatever the scale, the final evolution of a damming process is always the result of the interaction between factors connected to the dam-landslide and factors relating to the watercourse. Once the investigated natural phenomenon is known and the factors that physically determine its development are identified, it is possible to identify some relationships that can describe the possible formation of a dam and forecast its evolution.

Some attempts to describe the damming phenomenon are proposed, with the formulation of new geomorphological indexes that could be considered as improved versions of the state of the art indexes introduced above. Once again, the indexes are ratios composed by a numerator accounting for the barrier, and a denominator accounting for the stream. Ratios are realized through the systematic comparison between parameters summarizing the two natural systems. In this way, the factors of the expression are kept separate in order to graphically underline their influence on the final results. The proposed indexes are designed to meet the basic principles of easy and fast data collection, which are considered as being crucial during emergencies. Hence, the indexes are based on morphometric parameters that can be rapidly derived (e.g. with GIS software) from distributed data as satellite images and

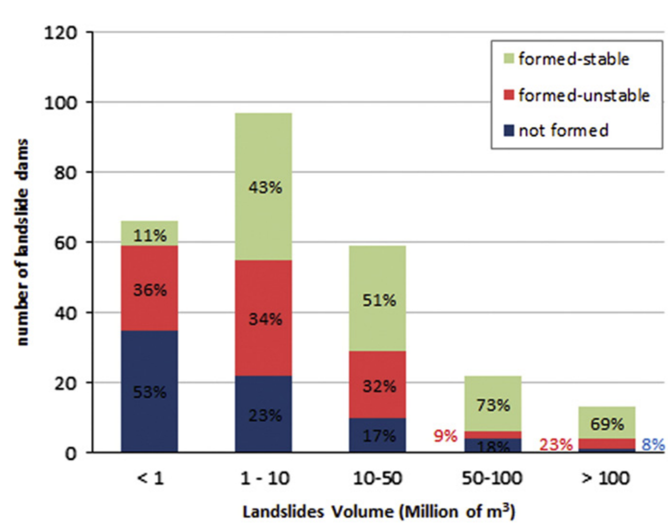

Fig. 1. Distribution of landslide dams volume according to the evolution classes and relative percentage.

Table 1
The t-test result of the Morphological Obstruction Index between the three classes of dam evolution. P(t): probability of the starting hypothesis that samples have a normal distribution; t: ratio of the mean to the standard error of the difference of the two groups.

t-Test result (MOI)		
Alpha = 0.05		
Not formed/formed-unstable	Not formed/formed-stable	Formed-unstable/formed-stable
$t = -4.2477$ $P(t) = 2.0331\ E-05$	$t = -5.5336$ $P(t) = 6.5369\ E-08$	$t = -2.4559$ $P(t) = 7.5224\ E-03$

DTMs (Kuo et al., 2011; Chen et al., 2014; Dong et al., 2014), which are easily available even on large areas.

2.4. Morphological Obstruction Index

One of the limitations of most part of the current indexes is that they have an engineering approach: they consider the problem as an artificial dam, without any account of the geo-morphological background of the environment. In order to take into account the morphological setting where the landslide interfere, a key parameter related to the river valley, the valley width, is evaluated. As a matter of fact, a landslide with relatively small volume can completely block a narrow valley with steep slopes, but it has low chance to achieve the same result in a wide floodplain. The valley width can be used to morphologically characterize the valley obstruction aptitude from a landslide. Fan et al. (2012) observed such a correlation between landslide volume and valley width for natural dam formation. Starting from these considerations, in order to contribute to the improvement of damming assessment analysis, we defined the "Morphological Obstruction Index", MOI:

$$MOI = \log(V_l / W_v) \tag{4}$$

where V_l represents the landslide volume (m^3) and W_v the width of the dammed valley (m).

2.5. Hydromorphological Dam Stability Index

The stability of an obstruction is related to the dam volume and the erosive capacity of the stream. The stream power (Ω) was suggested to use as the basic indicator of the energy of the stream by many authors (e.g. Bagnold, 1966; Baker and Costa, 1987; Dalla Fontana and Marchi, 2003). It represents the work that a river may do, and controls also the dammed lake filling speed. The stream power per unit channel length is expressed in Watt/m and presented as follows:

$$\Omega = \rho \cdot g \cdot Q \cdot S \tag{5}$$

with ρ the fluid density (in kg/m^3), g the acceleration due to gravity (in m/s^2), Q the discharge (in m^3/s), S the energy slope (m/m, which may be approximated by the local slope of the channel bed). In Eq. (5) there are two variable components: discharge (Q) and local slope (S). Channel bed slope can be easily extracted from digital elevation models. The discharge value Q is controlled by different factors, as climate and basin morphology, and cannot always be computed briefly. Moreover, it is difficult to assess its spatial distribution as a continuous spatial variable. Therefore, in the existing literature the stream power has been evaluated on a topographic basis and the discharge has been estimated using proxy parameters, such as the contributing catchment area (Knighton, 1999; Stock and Montgomery, 1999; Ermini and Casagli, 2003; Marchi and Dalla Fontana, 2005; Conforti et al., 2011). As an instance Moore et al. (1991) proposed the following simplified geomorphological formulation:

$$\Omega = A_s \cdot S \tag{6}$$

where A_s is the specific catchment area (km^2). Natural dams are very common in mountain or hilly valleys, which are characterized by narrow and with steep slopes. Within this context, this simplification can be used as a proxy for the river destabilizing action to the dam stability. Comparing this expression with the most significant parameter of the landslide, the volume, we obtain the "Hydromorphological Dam Stability Index", HDSI, expressed as follows:

$$HDSI = \log\left(\frac{V_l}{A_b \cdot S}\right) \tag{7}$$

where V_l is the landslide volume (m^3), A_b the catchment area upstream of the blockage point (km^2) and S the local longitudinal slope of the channel bed.

3. Results

To confirm the significance of the information provided by the two proposed new indexes, the data relating to the three main evolution classes underwent to a simple but effective test of statistical significance, the t-test.

The t-test takes into account two populations of data at a time from a zero starting hypothesis that the distribution of data within the two groups is equal to each other and the observed difference can be attributed to chance. The result of the t-test is the probability P(t) that 95% of the data verify the hypothesis. Thus, the lower the P(t) value, the greater is the statistical difference between the two populations. Conventionally, two populations are considered statistically distinct if the P(t) value is less than 0.1 for an alpha equal to 0.05.

Table 1 shows the results of the t-test for Morphological Obstruction Index carried out between the three classes of dam evolution. These low values confirm that the three groups of data are statistically distinct and the difference in their distribution cannot be attributed to chance.

Table 2
The t-test result of the Hydromorphological Dam Stability Index between the three classes of dam evolution. P(t): probability of the starting hypothesis that samples have a normal distribution; t: ratio of the mean to the standard error of the difference of the two groups.

t-Test result (HDSI)		
Alpha = 0.05		
Not formed/formed-unstable	Not formed/formed-stable	Formed-unstable/formed-stable
$t = 0.5535$ $P(t) = 0.2903$	$t = -4.304$ $P(t) = 1.4327\ E-05$	$t = -2.4559$ $P(t) = 1.1120\ E-06$

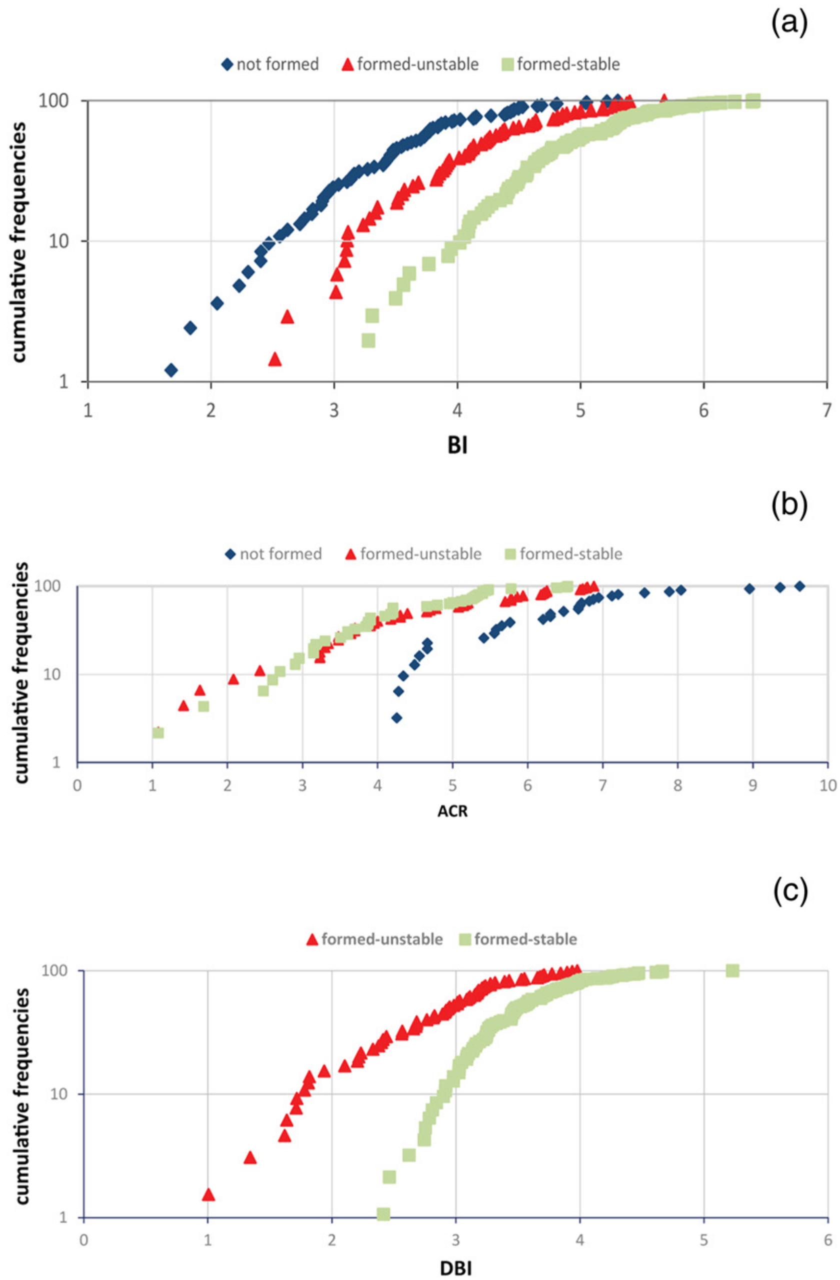

Fig. 2. Morphological analysis of Italian landslide dams, distinguished by evolution classes, using: (a) Blockage Index (according to Canuti et al. (1998)) value distribution; (b) Annual Constriction Ratio (Swanson et al., 1986) value distribution; (c) Dimensionless Blockage Index (Ermini and Casagli, 2002) value distribution.

The t-test results for the Hydromorphological Dam Stability Index, shown in Table 2, confirm the graphical observations. The data sets concerning not formed dams and formed-unstable are statistically too similar ($P(t) > 0.1$), whereas formed-stable dams are clearly distinguished from the other two data sets.

The results of the application of the state-of-the-art indexes are shown in Figs. 2 and 3. Fig. 2 shows the cumulative frequencies of the three evolution classes in order to evaluate the relative class distribution. Fig. 3 shows the Bi-logarithmic diagrams of the indexes focusing only on a particular aspect of the dam evolution. Where data pertaining to different evolution classes are distributed over distinct sectors of the graphic, some domains of existence can be identified. The boundaries of the domains are defined according to the threshold values reached by the data of the different evolution classes.

The Blockage Index, as formulated by Canuti et al. (1998), distinguishes the evolution differences of the Italian dataset with good approximation. Three different domains of existence can be recognized (Figs. 2(a) and 3(a)) as follows:

- Formation domain: $BI > 5.68$. Above the threshold value, only formed dams are present. Fig. 2(a) shows that all these dams are formed-stable apart from an exceptional case of formed-unstable dam;
- Uncertain domain: $3.00 < BI < 5.68$. In this domain, there are stable, unstable and not formed dams;
- Not formed domain: $BI < 3.00$. Below this value, the sector of the diagram is occupied by not formed dams. In this field, two exceptional cases of formed-unstable dams are also present.

The reliability of the diagram is greater in its marginal areas, while in the central “uncertain determination” domain, where 81% of cases fall, there is a strong uncertainty. The formation domain includes only 11% of the dams and the not formed domain 8%, with several incorrectly classified cases.

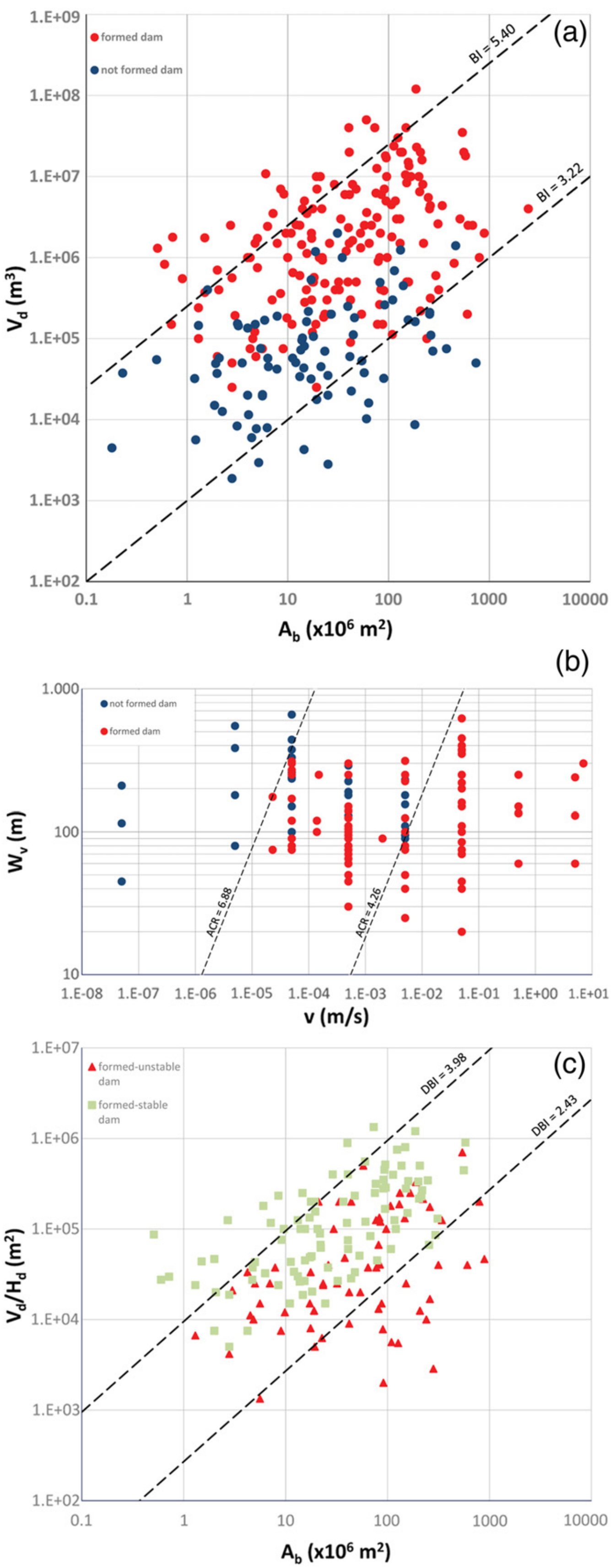

Fig. 3. Bi-logarithmic diagrams of Italian landslide dams, distinguished by evolution classes, according to: (a) ratio between landslide dam volume, V_d, and drainage basin area, A_b (Blockage Index, according to Canuti et al. (1998)); (b) ratio between valley width, W_v, and landslide velocity, v (Annual Constriction Ratio, according to Swanson et al. (1986)); (c) landslide dam volume and dam height plotted versus drainage basin area (Dimensionless Blockage Index, according to Ermini and Casagli (2002)).

Figs. 2(b) and 3(b) show the trend of the Annual Constriction Ratio Index for 123 of the censed cases. In the diagram of Fig. 2(b), the formed-unstable and formed-stable dams overlap and cannot be distinguished. Some threshold values useful for forecasting purposes are established and three main domains can be separated as follows:

- Formation domain: ACR < 4.26. This is the lower limit of not formed dams. In this domain only formed-stable and -unstable dams can be found;
- Uncertain domain: 4.26 < ACR < 6.88. In this domain the three evolution classes coexist together;
- Non-formation domain: ACR > 6.88. This is the upper limit of formed cases and is the domain with only not formed dams.

The overlapping area in the middle of the graphic contains 54% of the cases. Only a small part of the cases (37% of the total) have ACR < 4.26 and even smaller (9%) have ACR > 6.88.

The results of the application of the Dimensionless Blockage Index to the DataBase are represented in Figs. 2(c) and 3(c). Here, as for the Blockage Index, three main domains can be separated as follows:

- Stability domain: DBI < 2.43. Below this threshold value, only formed-stable dams are present;
- Uncertain domain: 2.43 < DBI < 3.98. Both formed-stable and formed unstable dams are present in this portion of the graph;
- Instability domain: DBI > 3.98. In this domain only formed-unstable dams are present.

The central area of uncertain definition is very broad and includes 76% of the reported cases, while both the Stability and Instability domains contain 12% of the total. The uncertain domain in Fig. 3(c) is wider compared to the one proposed in the original work of Ermini and Casagli (2002). In fact, the two limits identifying the different domains for the latter authors were DBI = 2.75 for the Stability domain and DBI = 3.08 for the Instability domain.

The application of the two new proposed indexes is shown in Figs. 4 and 5. Fig. 4, shows the cumulative frequencies of the three evolution classes, while Fig. 5 focuses on each stage of the dam evolution. Fig. 5(a), in fact, is focused on the Dam Formation, Fig. 5(b) on the Dam Stability.

The results of the Morphological Obstruction Index application are represented in the distribution diagram of Figs. 4(a) and 5(a). In Fig. 4(a) the collected cases are divided in three different domains of existence, as follows:

- Non-formation domain: MOI < 3.00. A landslide with index value lower then this boundary is not able to block the riverbed and evolves in a not formed dam;
- Uncertain Evolution domain: 3.00 < MOI < 4.60. In this area, the behavior of the dam is uncertain because, even if formed, it can evolve toward instability and collapse. If 3.00 < MOI < 3.83, a formed dam will be unstable. If 3.83 < MOI < 4.60, the formed dam can be stable, but in this domain also not formed and formed-unstable dam can be available;
- Formation domain: MOI > 4.60. Above this value, the valley is certainly blocked. Here the density, and thus the probability, of formed-stable dams is higher, however the dam can still evolve to an instability situation.

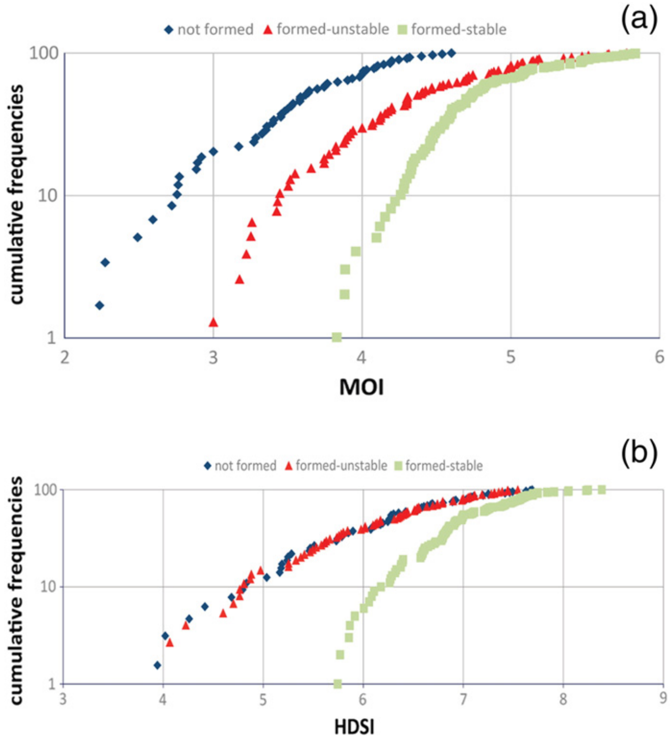

Fig. 4. Morphological analysis of Italian landslide dams, distinguished by evolution classes, using: (a) Morphological Obstruction Index value distribution; (b) Hydromorphological Dam Stability Index value distribution.

A similar result is shown in the bi-logarithmic diagram of Fig. 5(a), where landslide volume, V_l, and width of the dammed valley, W_v, are plotted. The index predicted the behavior of 233 landslide dams (78% of the total) with a rather narrow Uncertain Evolution domain, containing about 39% of the collected cases. The other two domains, the Non-formation and the Formation, contain 15% and 46% of the cases, respectively. Two dashed lines, a red one and a blue one, bound the shady red area of the Uncertain Evolution domain. The two lines are plotted to encompass the lowest formed and the highest not formed dam. The red dashed Non-formation Line represents the lower bound of the formed dams, both stable and unstable, and the upper bound of the Non-formation domain. Its equation is expressed as follows:

$$V_l' = 1.7 \times {W_v}^{2.5} \tag{8}$$

where V_l' represents the landslide volume (m^3) and W_v the width of the dammed valley (m). This volume value, V_l', is named "Non-formation volume" and is the minimum landslide volume allowing the dam formation, less than a landslide does not produces complete river obstruction at all.

The blue dashed Formation Line is the upper bound of the not formed dams and the lower bound of the Formation domain. It is expressed as follows:

$$V_l'' = 180.3 \times {W_v}^2 \tag{9}$$

Where V_l'', named the "Formation volume", represents the landslide volume (m^3) and is the boundary volume above which the river valley is definitely dammed.

The distribution diagram in Figs. 4(b) and 5(b) shows the result of the application of the Hydromorphological Dam Stability Index to the Italian landslide dams.

Three main domains can be highlighted in Fig. 5(b) as follows:

- Instability domain: HDSI < 5.74. It is an upper boundary for not formed and unstable dams, determined by the lower HDSI value reached by the stable dams. Below this value the landslide is not able to form a stable dam and even if it blocks the valley, the dam is unstable;
- Uncertain Determination domain: 5.74 < HDSI < 7.44. In this area the evolution of the dam is uncertain. Even if the blockage is complete, it can be unstable and collapse;
- Stability domain: HDSI > 7.44. It is a lower boundary for stable dams, defined as the higher HDSI value assumed by the not formed and unstable dams. The valley is certainly blocked and the dam is stable.

The Uncertain Determination domain is rather extended, with 66% of the cases and the Stability domain is quite narrow, with 20% of the dataset, while the Instability domain counts 14% of the total.

4. Discussion

Comparing the results of the literature indexes and newly proposed one, we can observe that the latter show an improvement in the prediction effectiveness. About the assessment of dam formation, the dams with an uncertain evolution pass from 81% or 54% of the Blockage Index and Annual Constriction Ratio to 39% of the newly proposed Morphological Obstruction Index, without incorrectly classified cases as for the Blockage Index. The dam stability prevision is enhanced too: the Uncertain domain is reduced from 76% (using Dimensionless Blockage Index), to 66% (using Hydromorphological Dam Stability Index). The good performances of the new proposed indexes can be explained with the geomorphological meaning of the involved parameters.

With the increase of the value of the Blockage Index (Fig. 2(a)), the dam will evolve toward a state of greater stability. Thus, landslides with larger volumes and smaller watershed result more likely in complete formed dam. Conversely, a small volume of material and an extended watershed area are not likely to completely block the river. The Blockage Index was originally conceived to assess the landslide dam formation, but when applied to our national-scale case of study, it proved to be unreliable, as the domain of uncertain classification was very broad. While the analysis of the stability of a formed dam with known volume is immediate, the assessment of the volume of a sliding landslide is an important step to assess the formation of a possible river obstruction and its stability. This can be carried out, also during emergency, with several remote sensing techniques and by GIS analyses (Du and Teng, 2007; Kuo et al., 2011; Tofani et al., 2013; Tseng et al., 2013; Chen et al., 2014; Dong et al., 2014).

The Annual Constriction Ratio data trend (Fig. 2(b)) shows that increasing the index value, the possibility of a stream blockage decreases, while the number of not formed dams increases. This is also clarified in Fig. 3(b), where only higher velocity landslide movement, which has the energy to go through the entire valley, can block widest river. This index can be useful just for a rough estimation because it has a good reliability only in the extreme areas and the landslide velocity usually cannot be measured with accuracy. Other methods, more direct and with a more certain input data, should be preferred.

In the same way, the Dimensionless Blockage Index (Fig. 2(c)) is more reliable in the marginal areas of its diagrams. Only sliding material with high volume/height ratio can realize stable dam in rivers with extended catchment area (Fig. 3(c)). Vice versa, low ratio dams evolve into unstable condition even in rivers with small catchment area. The larger dataset we use may explain the differences between the DBI results proposed in this work and the original study of Ermini and Casagli (2002). The DataBase accounts for a wider environmental

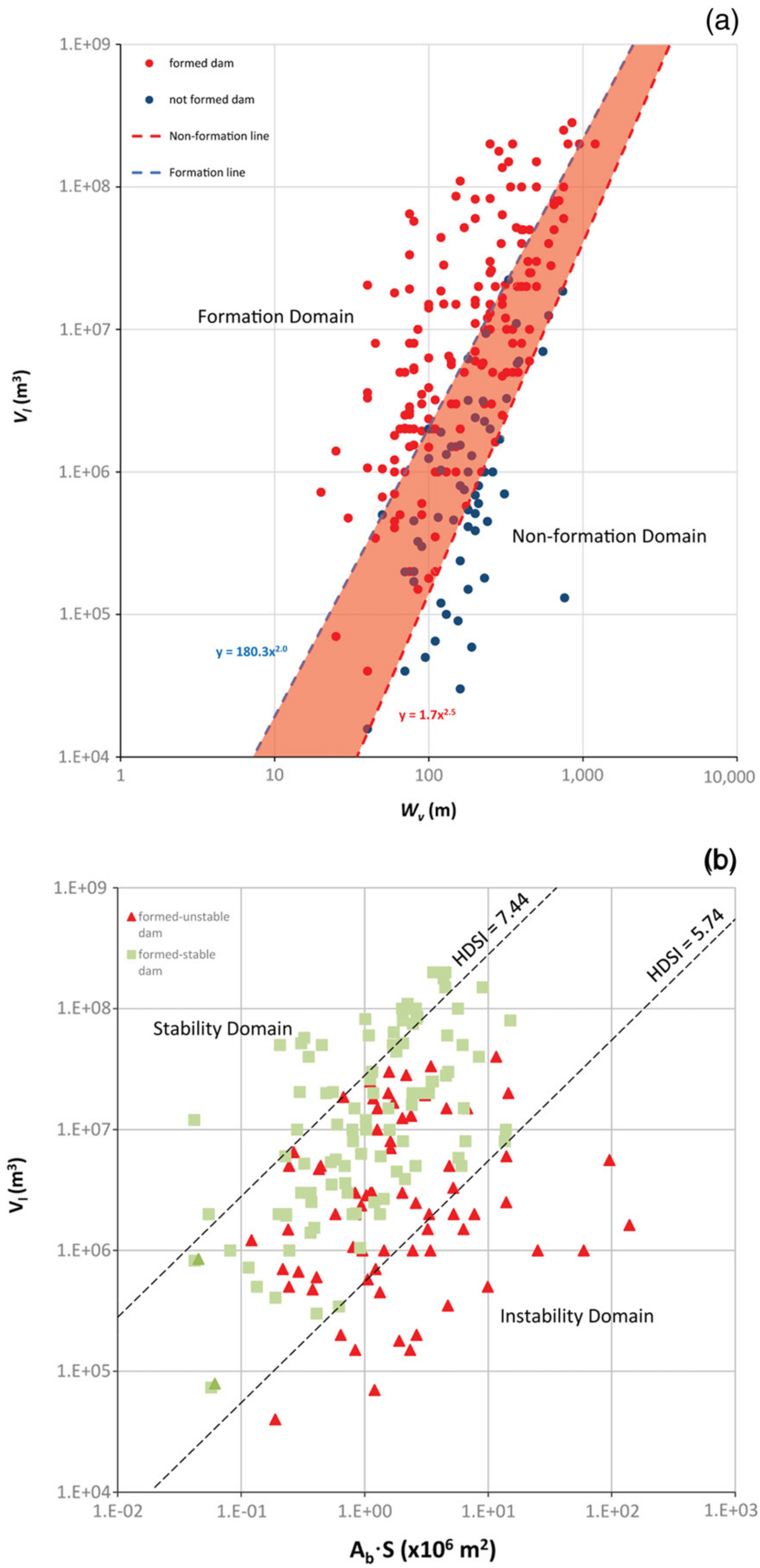

Fig. 5. Bi-logarithmic diagrams of Italian landslide dams, distinguished by evolution classes, according to: (a) plot of the ratio between landslide dam volume, V_l, and valley width, W_v; (b) plot of the ratio between landslide dam volume, V_l, and derived stream power, $A_b \cdot S$.

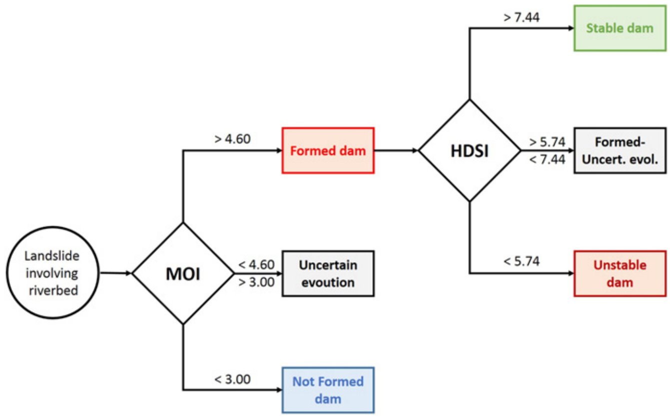

Fig. 6. Schematic flow diagram of the operational methodology to evaluate landslide dam formation and stability employing the Morphological Obstruction Index (MOI) and the Hydromorphological Dam Stability Index (HDSI).

variability, therefore can be considered more representative for the formulation of a general rule. About the index formulation, it is not always useful to merge too many variables: often, even if their importance as individual factors is known, their mutual influence is not completely understood. We can argue that the dam height is redundant, since it is explicitly present at the numerator and implicitly at the denominator (as part of the volume), although it is justified as a matter of theory. Despite this, the index can be a useful tool for carrying out preliminary forecasting on landslide dam stability.

The results of the new Morphological Obstruction Index shown in Fig. 5(a) allow performing a morphological estimation of landslide ability to block a river. According to the cases distribution of Fig. 5(b), assuming the same width of the valley, we can state that the larger the volume of the landslide, the greater the damming capacity.

An attempt of correlation between landslide volume and contributing catchment area as a morphological proxy for discharge is proposed in the diagrams of the Hydromorphological Dam Stability Index (Figs. 4(b) and 5(b)). It is possible to use the diagrams as forecasting tool for the stability of the dams. Even with a wide uncertain evolution area, as the index value increases the general stability of the dam also increases. The high climate variability in the Italian territory may be responsible for the wide uncertain domain. The two newly proposed indexes can be used in conjunction to forecast the final stage in which a landslide dam will evolve. Fig. 6 shows this procedure which can be displayed as a flow chart composed by two subsequent steps. In the first step, MOI is used to assess if the landslide will form a dam or not. If the result is a formed dam, in a second step the HDSI is used to assess the dam stability. This procedure can be applied over large areas e.g. to forecast hazard scenarios, for planning activities, or during emergency response.

As the Uncertain Determination domain of the HDSI is rather wide, many cases will result as "Formed-Uncertain evolution". An assessment of the formation probability of a stable dam can be derived through a graphical method, comparing the relative frequencies of the evolution classes in Fig. 4(b). The Index formulation itself does not allow a direct assignment of an occurrence probability value of a single scenario. It is possible, instead, through the knowledge of the values assumed by the index in the past cases, to quantitatively assess the formation probability of a stable dam P(FS). Therefore, if the Hydromorphological Dam Stability Index value is assessed, the probability of formation of a stable dam can be expressed as follows:

$$P(FS) = \frac{(100 - FS_y)}{(100 - FS_y) + (100 - FU_y) + (100 - NF_y)} \tag{10}$$

with FSy, FUy and NFy are the ordinate values of Formed-Stable, Formed-Unstable and Not Formed dams in Fig. 4(b) for the corresponding HDSI value. So, for HDSI value bigger than 7.67 the probability of a stable dam is 100%, because FUy and NFy assume a value of 100 and the resulting equation become $P(FS) = (100 - FSy)/(100 - FSy) = 1$.

Generally speaking, the main drawback of the proposed methodology is the subjectivity in the selection the parameters that define the morphological indexes: the choice of the parameters followed a heuristic approach based on expert judgment, involving literature review and personal considerations of the authors. One of the main reasons for the heuristic choice of parameters, shared also by all the relevant literature on the topic, is that statistical methods for the quantification of relative variable importance based on multivariate techniques must rely on a large amount of validation data. These are clearly not available at the moment for what concerns time series of landslide dam evolution cases. To rely on such scanty ground truth would probably generate spurious variable importance rankings so that a heuristic approach is more advisable in the specific case. In addition, there is no evidence that the proposed indexes could have similar performances if applied outside Italy. These two drawbacks could be addressed in future stages of the research to ensure a stronger objectivity and wider applicability to the proposed methodology.

5. Conclusions

Landslide dams are the result of the complex interaction between watercourse and slope dynamics. An effort to assess the damming hazard with practical geomorphological tools has been presented. Two main issues concerning this phenomenon are discussed: the formation of a dam and its evolution. An analysis on a large dataset (300 landslide dams) extended all over Italy using geomorphological indexes was performed. Two new indexes, i.e. Morphological Obstruction Index (MOI), and Hydromorphological Dam Stability Index (HDSI), designed to meet the basic principle of an easy and fast data collection, were proposed. They are based on landslide volume V_l, as well as valley width W_v, and a geomorphological proxy of the stream power ($A_b \cdot S$), respectively. These parameters are spatially distributed attributes of the landscape morphometry and can be easily defined as spatially continuous variables from commonly available data such as satellite images and DTMs. Some aspects of previous methods, as the easy availability of the input data and the prediction effectiveness, were satisfactorily improved. Encouraging results came from the formulation of the Morphological Obstruction Index as 61% of the dataset were correctly classified. The formulation of the index allows performing a reliable analysis and provides a good estimator to forecast the dam formation for a landslide blocking a river. The Hydromorphological Dam Stability Index can estimate the long-term stability of dams, thus it can be applied to formed dams to discriminate between "formed stable" and "formed unstable".

A fast methodology employing these indexes is proposed as a useful tool to carry out a preliminary assessment of the evolution of landslide dams. On a first step, Morphological Obstruction Index can be used to discriminate between formed and not formed dams. Then, Hydromorphological Dam Stability Index can be employed to verify if the formed dams are stable or unstable. When a classified case is placed in the Formed-Uncertain evolution domain, a graphical methodology is proposed to assess the formation probability of a stabile landslide dam. This procedure can be used for forecasting and planning purposes at basin or smaller scale and further developments of the research could lead to define a damming susceptibility methodology based on these morphometric parameters. The climatic, lithological and morphological variability covered by the study area (about 3×10^5 km^2 of extension) and the extensive used dataset, allow the proposed investigations to be considered representative at least all over Italy, while the effectiveness of the proposed procedure in other settings should be evaluated before application.

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